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COMPARATIVE STUDY OF THE HEAT TRANSFER OF A NOZZLE BLADE PROFILE IN A WIND TUNNEL AND IN AN AIR TURBINE

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16. Abstract

Investigation of the local and mean heat removal from a textolite nozzle blade in a wind tunnel with a thermal counter-current, and in the second cascade of an air turbine. Permalloy strips with wires glued on the nozzle blade were heated by a DC current during the tests. The flow turbulence level was markedly higher behind the rotor of an air turbine than in a typical wind tunnel. The mean heat removal coefficient increased with increasing Reynolds number. The laminar and transition boundary layers were appreciably smaller on a turbine nozzle blade than in the wind tunnel.

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COMPARATIVE STUDY OF THE HEAT TRANSFER OF A NOZZLE BLADE PROFILE IN A WIND TUNNEL AND IN AN AIR TURBINE

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The laws of heat exchange between a profile and the medium flowing around it have been investigated in a number of works [4, 8]. An overwhelming majority of the experimental investigations have been performed with plane arrays of profiles mounted in wind tunnels with varying degree of preliminary flow preparation. The data presented by several authors on the intensity of heat exchange averaged over the profile under real turbine conditions are very contradictory. For example, according to the data of works [5, 6], the dependences obtained experimentally in a real turbine agree well with the results of investigations carried out on plane arrays, while according to the data of works [7, 9], because of an increased degree of flow turbulence in the real turbine, the intensity of heat transfer is 1.4 to 2.0 times greater than in the plane array of profiles in the wind tunnel. /61*

Because of the absence in the literature of sufficiently reliable data on the laws of local heat transfer on the profile, two versions of calculations are usually carried out when determining the temperature fields of turbine blades: the first is to assume the possibility of the existence on the profile in the real turbine of a laminar boundary layer with a transition to the turbulent and the other, the existence of only a turbulent boundary layer on the profile.

*Numbers in margin indicate pagination of original foreign text.

The necessity of carrying out different calculations makes the development and determination of the effectiveness of new cooling systems for blade sets of gas turbines significantly more difficult, especially since it is impossible to evaluate the reliability of the temperature fields thusly obtained.

Since the further development of stationary gas turbine construction depends mainly on successes in creating cooled blade sets, a detailed study of the effect of the level of flow turbulence on the intensity of heat transfer at a nozzle blade profile was specified in the combination of works on the investigation of heat exchange in standard elements of cooling systems, being carried out at the Institute of Technical Thermal Physics of AN UKrSSR. /62

This article discusses the basic results of the first stage of these investigations performed at the Turbomotor plant (TMZ), during which a comparative study of local and average heat transfer on nozzle blades was carried out in a wind tunnel for plane arrays and in an air turbine, where the blades under study were placed behind the rotor, i.e., under conditions typical for the second-stage nozzle set.

The degree of flow turbulence was not measured in either installation in experiments carried out in 1966; however, it is quite reasonable to assume that its value in the air turbine is close to values typical for real turbines, and in the wind tunnel — to values typical for laboratory installations of such types.

The experiments were carried out on an actual-size guide blade of the first stage of the high pressure turbine installation GT-6-750 of TMZ.

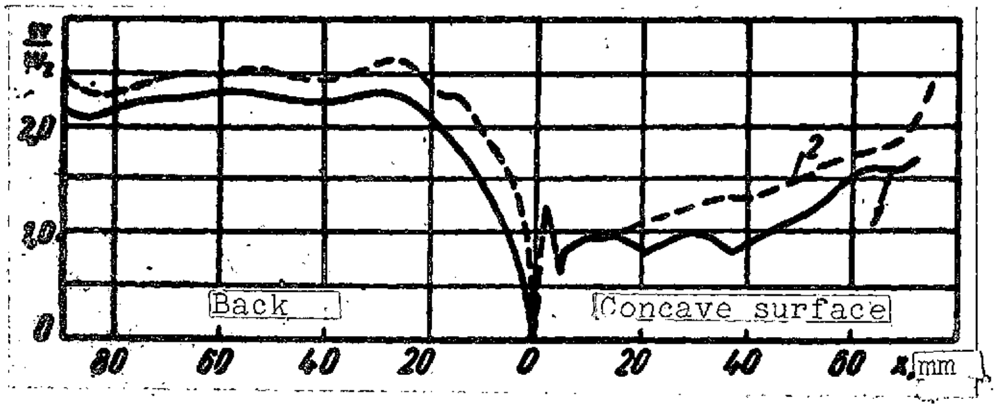

Figure 1. Graph of the distribution of the relative velocity (w/w_z) over the blade profile.
1- experimental data (from measurement of the static pressures over the profile); 2- calculation of potential flow.

The investigated blade had a chord of 72 mm (with an array spacing of 53 mm), a geometric angle of incidence of 90°, and of departure of 27°; a radius of curvature of the incidence edge of 5 mm, and of departure of 0.5 mm.

The aerodynamic quality of the blade can be judged from Figure 1, on which the distribution of the relative flowrate (w/w_z) over the profile is presented. /63

The investigation of heat transfer on the blade surface was carried out with a thermal counter-current. The blade (Figure 2) made of textolite with three bands of permalloy 65-10 glued to the contour of the profile was heated with an electric current.

The total width of the bands was 40 mm. Electric current was supplied to the bands being heated along copper wires 4 x 1 mm in cross section mounted flush with the profile in grooves on the convex side of the blade close to the incidence

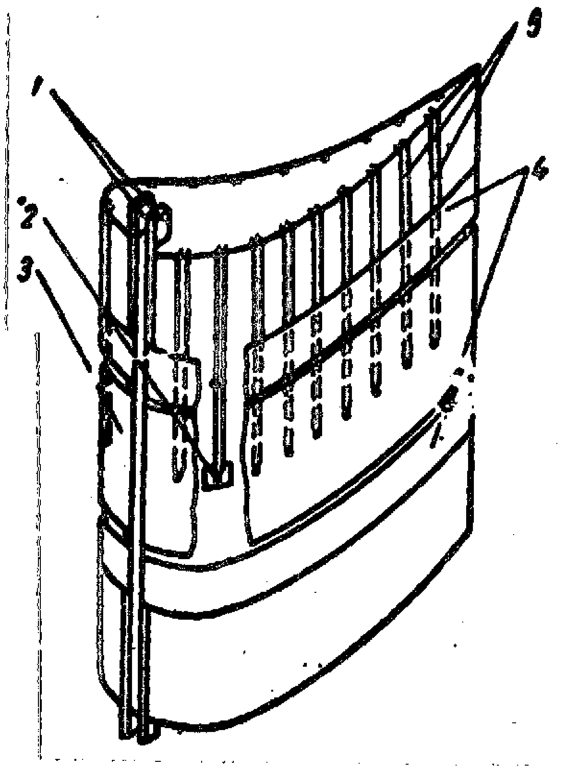

Figure 2. Structural diagram of the heated blade.

1- current conductor leads; 2- electrical insulation (mica sheet); 3- main heated band; 4- heat insulation sheets; 5- thermocouples.

edge. One of the free ends of the wires was used for connecting the power leads, the opposite site for measuring the voltage drop on the band. To measure the temperatures of the band under study, 20 precalibrated chromel-kopel thermocouples were mounted in milled slots in the countour of the profile under the band. The EMF of the thermocouple was measured with the EPP-0.9 potentiometer with a measurement range 0 — 100° C. For electrical insulation of the thermocouple junctions from the band being heated, a thin mica spacer was placed between the junction and the band.

The bands glued to the blade were heated by direct current (with voltage of 1.2 to 2 V) from a VSG-3a rectifier. Thermal loading of the blade was regulated with the LATR-1M laboratory autotransformer placed before the rectifier. To maintain a stable thermal mode, supply of the whole installation was accomplished through the USN-350 voltage stabilizer.

The electrical power expended in heating the blade was /64 determined by measuring the voltage on the lines with the D-523 voltmeter (class 0.5) and measuring with the M-104A millivoltmeter (class 0.2) the voltage drop at a calibrated resistance (class 0.5) mounted in the blade supply circuit.

The thermal flux density at the blade under study was determined from the expended electric power:

$$q = \frac{Iv}{F}, \tag{1}$$

where I is the current in the electrical circuit of the blade; v is the voltage on the lines of the bands being heated; and F is the total area of the bands.

The local values of the heat transfer coefficient over the profile was calculated from the dependence:

$$\alpha = \frac{q}{t - t^{*}_{air}}, \tag{2}$$

where t is the local temperature on the profile; t^{*}_{air} is the air drag temperature at the input to the array.

The same textolite blade with the same preparation was used for the experiments in the wind tunnel and in the air turbine.

The experimental method for determining the local values of the heat transfer coefficients on the profile of the blade assumes the heat flux from the blade being heated to the air is constant over the length of the band. Thus, the error in determining α will have contributions from errors in measuring the profile-averaged value of the heat flux, the difference in the blade and air temperatures, and also errors arising as a result of the effect of factors disrupting the constancy of the thermal emission.

The error in determining the average heat flux and temperature difference is found as a sum of the relative errors in measuring the parameters defining these quantities. The relative error in measurement is about 0.7% for the current, about 0.7% for the voltage drop, and about 0.6% for the temperature head. This error is about the same for all points at which the heat transfer coefficients are determined. The same error (about 2%) is also typical for determining the profile-averaged values of the heat transfer coefficient.

The factors disrupting the constancy of thermal emission /65
over the contour of the profile include the flow of heat through the body of the blade and along the band; radiation from the heat transfer surface to the neighboring cold blades; a change of the electrical resistivity along the length of the band, and also a change in the thickness and width of the band.

It is evident that the error contributed by these factors will be different for each point of the profile at which α is determined. The magnitude of these errors depends mainly on the absolute value of the temperature at the given point and the temperature gradient.

A calculation of the relative errors in determining α, carried out for several modes according to the technique presented in [1], indicates that the maximum error for all points is 4 — 5%, with the exception of two points, whose maximum error is 9 — 11%.

The streamline mode of the profile was evaluated in the experiments by the Reynolds number calculated from the average flowrate in the array, the chord of the profile and the viscosity determined for the air temperature at the input of the array. The average flowrate in the array w_{av} was determined as the arithmetic-mean of the velocities at the input and output of the array. The output flowrate from the array w_2 was determined with the help of gasdynamic functions from the total and static pressures measured at the output in the experiments, and the flowrate at the input to the array w_1 was found from the output velocity w_2 and the experimentally measured flow departure angle from the array:

$$w_1 = w_2 \sin \alpha_2. \tag{3}$$

The wind tunnel used for the study was designed for plane arrays and had the usual system for flow pre-preparation.

Batching capacity of the experimental single-stage air turbine was about 40%, thus, the height of the blade could be increased to 60 mm for the available air flowrate. The diameter of the turbine rotor at the average section of the blades was 540 mm. The power developed by the turbine was absorbed by a disc-type hydraulic brake. To stabilize the mode of operations of the turbine, water was supplied to the hydraulic brake under a hydrostatic head from a special tank, in which the level was automatically maintained constant.

The turbine provided long-term stable operation in the range of 1500 — 4000 rpm.

To compare the results of the experiments carried out in the installation for plane arrays and in the air turbine, it is necessary to know how the local values of the heat transfer coefficients are distributed over the profile for the same /66

Reynolds numbers. However, it is difficult to specify precisely the Reynolds number mode beforehand in the experiment. Thus, the experiments in both the wind tunnel and in the turbine were carried out with the Reynolds number varying from $1 \cdot 10^6$ to $6 \cdot 10^6$. Curves of the dependence Nu = f(Re) were constructed from the results of these experiments for each point (using the graph of the velocity distribution over the profile). This permitted determining and then comparing the values of the local Nusselt numbers for the same values of the Reynolds numbers.

This method for processing the original experimental data permits taking into account the inevitable changes from experiment to experiment of the air temperature, and also simplifies determining the mode of flow in the boundary layer about the contour of the profile.

All the experiments, both in the wind tunnel and in the air turbine, were carried out with shockless flow over the blade, and also with small temperature differences (no more than 70°) between the heated blade and the area.

Figure 3 presents the data on the distribution of the local heat transfer coefficient over the blade profile, obtained for tests in the installation for plane arrays and in the air turbine, and Figure 4 is a graph of the dependence of the relative coordinate of the beginning and end of the transition region on the Reynolds number (constructed on the basis of analyzing the exponent n in the dependence $Nu = cRe^n$) with tests in the wind tunnel (dashed lines) and in the air turbine (solid lines).

It is seen from examination of these figures that, in the wind tunnel, the transition region from the laminar mode to the turbulent mode on the concave surface of the profile begins at

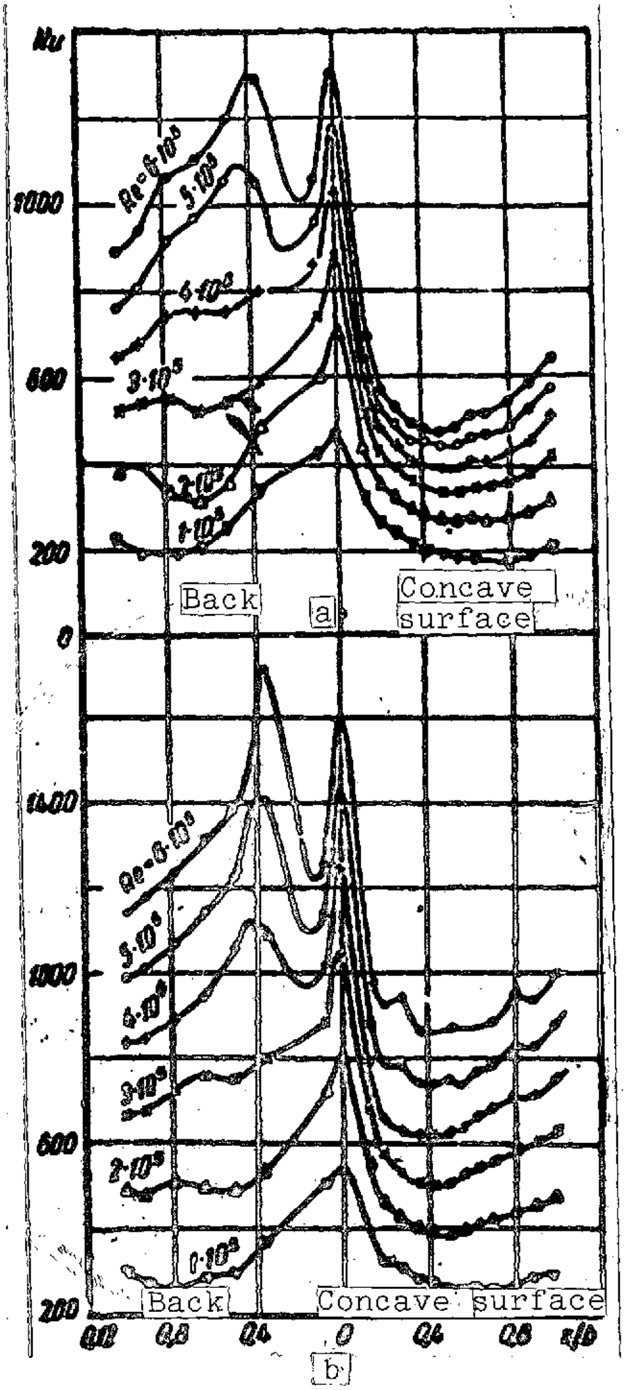

Figure 3. Graphs of the local heat transfer coefficient distribution over the blade profile, depending on the Reynolds number from data of tests in the wind tunnel (a) and in the air turbine (b).

a distance x/l = 0.55 from the incidence edge of the blade. The coordinates of the beginning of the transition region are almost independent of the Reynolds number in the investigated range. A turbulent boundary layer was not observed on the concave surface in the experiments.

The exponent of Re on the laminar portion is 0.42 — 0.47 which, in all probability, must be explained by the presence of boundary layer detachment in this zone (cf., Figure 1). The transition mode on the concave surface develops under conditions of array convergence. The exponent of the Reynolds number, as the experiments indicate, is in the range 0.56 — 0.644 /67 (increasing monotonically toward the departure end).

Investigations carried out in the air turbine indicate that the dependence of the coordinate of the beginning of the flow transition region in the boundary layer on the Reynolds number clearly appears on the concave part of the blade. The

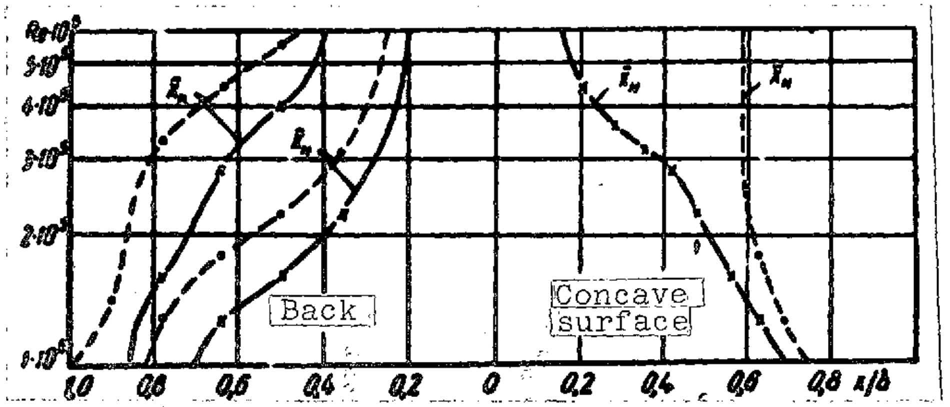

Figure 4. Graph of the dependence of the relative coordinates of the beginning $\bar{x}_i$ and end $\bar{x}_k$ of the transition region of flow in the boundary layer on the Reynolds number.

transition point shifts toward the incidence edge of the blade with increasing Reynolds number. The laminar portion is then characterized by the exponent n = 0.5.

The dependence of the coordinates of the beginning and end points of the flow transition region in the boundary layer on the Reynolds number is more clearly expressed on the back of the profile than on the concave part, both under the conditions of static flow, as well as under the conditions in the air turbine. The shift of these points toward the incidence edge with increased flow turbulence at the input for larger Reynolds numbers is less than on the concave part of the blade. Thus, even under conditions of increased low turbulence at the input to the array, a significant part of the profile remains filled with a laminar boundary layer.

By comparing the picture of the distribution of the heat transfer coefficient obtained from the investigation in the air turbine (Figure 3b) and in the wind tunnel (Figure 3a), it can be seen that the heat transfer level has grown significantly. /68

An increase of the heat transfer intensity on the profile was observed for all modes of flow in the boundary layer. Thus, it is impossible to explain the increase of the heat transfer coefficients averaged over the profile in the real turbine (increased turbulence at the input to the array) exclusively by the change of the coordinates of the transition region. In all probability, the explanation should also be found in the change of the thickness of the boundary layer.

It can also be noted for comparison that the growth of the heat transfer coefficient appears somewhat differently for the different portions of the profile and for different values of the Reynolds number. In particular, the heat transfer coefficient on the back increases by 20 — 30% in the air turbine, whereas on the concave part, the heat transfer intensity increases by 40 — 70%.

Larger values of the growth of the heat transfer coefficient correspond to larger values of the Reynolds number on the concave part of the blade, whereas on the back of the blade, the converse is observed: the larger the Reynolds number, the lower the growth of heat transfer intensity.

In performing the experiments in the wind tunnel, a series of experiments was carried out with a network of 1.5 mm diameter wires with a mesh of 10 x 10 mm placed at a distance of 1.5 times the chord from the array. These experiments indicated that the mesh had practically no effect on the heat transfer coefficient distribution over the profile or on its value averaged over the profile.

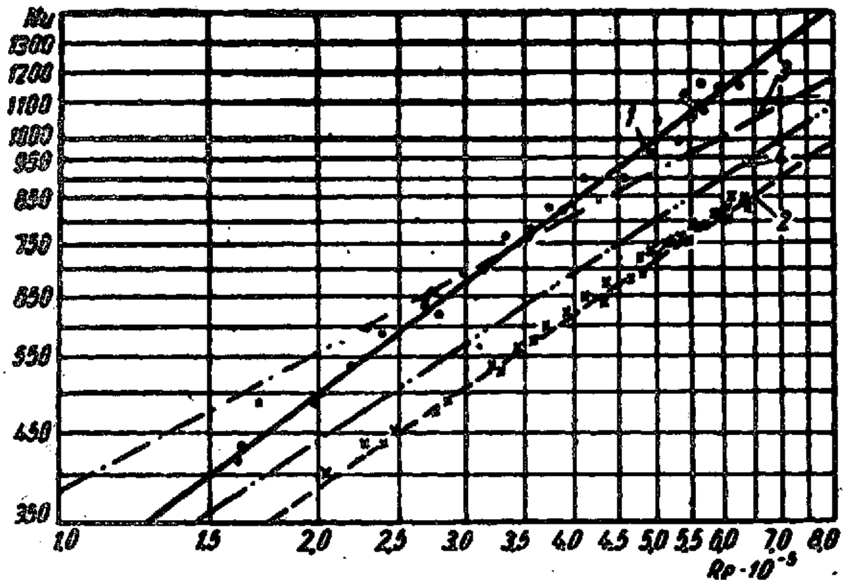

Figure 5. Graph of the dependence of the profile-averaged heat transfer intensity on the Reynolds number.

1- data from the air turbine; 2- data from the installation for plane arrays; 3- data from [3]; 4- data from [2].

By averaging over the area, a graph was constructed for the dependence of profile-averaged values of the heat transfer coefficient on the Reynolds number (Figure 5). For the array in the wind tunnel, the dependence has the form: /69

$$Nu = 0,12\, Re^{0,666}, \tag{4}$$

and for the same array in the air turbine:

$$Nu = 0,0507\, Re^{0,754}. \tag{5}$$

The dependences obtained by K. Bammert [2] and at the Kazan Aviation Institute [3] are also presented for comparison in Figure 5. As is seen in this figure, the dependence obtained with increased turbulence at the input to the array differs significantly from the analogous dependences obtained for the array in the wind tunnel. The greatest differences are observed for large Reynolds numbers, which characterize contemporary turbomachines.

These experimental data rather convincingly indicate the marked effect of the flow turbulence level on the magnitude and distribution over the profile of the local heat transfer coefficients, thus further investigations of the mechanism and laws of this effect must be considered extremely urgent. /70

The following conclusions can be reached on the basis of this investigation:

1. The flow turbulence level behind the rotor of the air turbine is significantly higher than in the typical wind tunnel for plane arrays of turbine profiles.

2. Increase of the level of flow turbulence in front of the input to the array leads to an increase of the heat transfer intensity between the profile and the medium flowing around it. The profile-averaged heat transfer coefficient increased by 30% for $Re = 2 \cdot 10^5$, and by 45% for $Re = 7 \cdot 10^5$.

3. The extent of the portions occupied by laminar and transition boundary layers is significantly less on a nozzle blade in a real turbine than in a wind tunnel. Completely turbulent flow around the profile was not observed in these experiments.

4. To obtain generalized criteria on the local heat exchange, it is necessary to have available some additional data, in particular on the degree of flow turbulence depending on the mode and structural parameters.

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